Effects of Fertilization and Irrigation on Root Numbers in a Red Pine Plantation[1]

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A core sampling technique was used for the investigation of root numbers in a 42-year-old red pine (*Pinus resinosa* Ait.) irrigation – K fertilization experimental area of a K deficient sandy outwash plain in the southeastern Adirondack Mountain Region of New York. Soil cores were collected from plots, 6 years after initiation of treatments, at 0–15 and 15–30 cm depths, using a 5.2 cm diameter corer. Roots were separated from soil cores by a sieving technique. Root tips, including each tip of mycorrhizal structures, were counted by classes established on the basis of morphological characteristics. Numbers of root tips were greater under nonfertilized than fertilized plots, and greater under irrigated than nonirrigated plots. This response pattern did not follow that of wood volume increment, which was greatest in fertilized plots, but was similar to the previously reported pattern in soil microarthropod numbers. The great natural variation observed suggests that root tip numbers may be highly sensitive to changes in soil conditions. Calculated sampling intensity, based on the variance estimates, and specific levels of probabilities (α and β) and allowable sampling error (ϵ), indicated the need for high numbers of samples.

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On s'est servi d'une technique d'échantillonnage utilisant un emporte-pièce pour l'étude du nombre de racines dans une aire expérimentale, en peuplement de pin rouge de 42 ans, soumise à l'irrigation et à la fertilisation potassique. La station est une plaine d'épandage fluvio-glaciaire sableuse, déficiente en potassium, dans la partie sud-est des Adirondacks de l'état de New York. Les prélèvements de sol ont été faits dans les parcelles six ans après le début des traitements, à une profondeur de 0 à 15 cm et 15 à 30 cm, au moyen d'un emporte-pièce de 5.2 cm de diamètre. Les racines ont été subséquemment isolées par tamisage. Les radicelles, y compris celles qui étaient mycorrhizées, ont été dénombrées par classes selon leurs caractères morphologiques. Le nombre de radicelles était plus grand dans les parcelles non fertilisées que dans les parcelles fertilisées et plus élevé dans les parcelles irriguées. Ce type de réponse ne suivait pas celui de l'accroissement en volume de bois, lequel était le plus élevé dans les parcelles fertilisées, mais concordait avec des obsrvations antérieures sur le nombre des microarthropodes dù sol. La forte variation naturelle observée suggère que le nombre de radicelles peut être très sensible aux changements de conditions du sol. Le calcul de l'intensité d'échantillonnage, basé sur les estimations de variance et les niveaux de probabilité spécifiques (α et β) aussi bien que l'erreur permise d'échantillonnage (ϵ), soulignent la nécessité de recourrir à un nombre élevé d'échantillons.

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Soil conditions have a pronounced influence on the abundance of tree roots and their morphology. Indurated layers, gleyed or humus-rich horizons, all markedly affect root development. Cultural treatment, producing changes in the level of soil aeration, nutrient availability, or moisture status can also influence root abundance and distribution. Under a variety of site

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conditions, fertilization of forest trees has produced increases in root growth (Den Uyl 1944; Auten 1945; Rennie 1953; Yeatman 1955; Brüning 1959; Kern *et al.* 1961; Bucholz and Neumann 1964; Zöttl 1964; Heinsdorf and Schulzke 1969; White *et al.* 1971). Most of these responses to fertilization were on sites deficient in the nutrient element to which root responses were recorded, but it is not always clear whether the root growth response was accompanied by increased above-ground tree growth. Meyer (1967) reported that the number of tree root tips per 100 cm^3 of soil increased with decreasing soil fertility. According to Meyer and Göttsche (1971), high numbers of root tips in the upper soil horizons under European beech (*Fagus sylvatica* L.) stands were indicative of site deterioration. Abundant development of mycorrhizal short roots is essential for tree growth on infertile sites (Hatch 1937; Harley 1969; Zahner 1968). Zöttl (1964) expanded the view of site relationships to include fertilizer response. He concluded that on relatively productive sites, a fertilizer-produced stem-growth increment was accompanied by a minimal increase in root growth measured as weight of roots less than 2 mm diameter to 10 cm soil depth. On infertile sites, however, the above-ground response to fertilization was associated with a large increase in root activity.

Under conditions of moisture stress, root extension may be inhibited directly (Kramer 1956, 1969; Eavis and Payne 1969) or indirectly through mechanical impedance, particularly in soils of high bulk density (Zahner 1968; Eavis and Payne 1969). Fine roots are particularly sensitive to soil moisture, becoming dessicated and dying under conditions of such stress. Larger roots, though less sensitive to soil moisture stress, do experience accelerated suberization under such conditions (Lyr and Hoffman 1967; Kramer 1969). Root development is often controlled by soil oxygen concentration, particularly in fine textured soils, and is inhibited by inadequate soil aeration. Thus, response of roots to irrigation may be confounded by the effect of irrigation on soil oxygen levels (Hilgeman and Reuther 1967).

Information on changes in root growth resulting from cultural treatment could contribute significantly to the characterization of treatment effect. A measure of the absorbing capacity of the root system in the upper soil horizons is relevant to the study of stand response to the surface application of plant nutrients and water. Studies on root development in red pine (*Pinus resinosa* Ait.) have shown a high concentration of roots in the forest floor and A horizon (Day 1941; Leaf *et al.* 1971). In this study, number of root tips was selected as an index of root absorbing capacity. The objective of the study was to measure the effect of fertilization and irrigation on root tip numbers in the surface soil horizons of a red pine stand.

Materials and Methods

The investigation was conducted on a fertilization–irrigation study area in a 42-year-old, 2 × 2 m red pine plantation. The site has been previously described in detail (Heiberg and Loewenstein 1958; Leaf and Leonard 1967; Leaf *et al.* 1970). The soil is a deep, loamy coarse sand (Hinckley series) with Ap and B solum horizons ranging from 14–24 cm, and 28–46 cm, respectively. Organic matter concentrations of the Ap range from 4.0 to 6.9%. The forest floor, prior to any treatments, included an L layer of 1.70 cm mean thickness and bulk density of 0.045 g/cm^3, and combined FH layer of 1.45 cm mean thickness and bulk density of 0.105 g/cm^3 (Stutzbach *et al.* 1972).

The fertilization treatment consisted of a single application of commercial grade muriate of potash broadcast in May 1966 at the rate of 448 kg elemental K/ha. Irrigation was initiated in 1966 with seven applications of water through the course of the growing season. Applications, each of which was 5 area cm of water, were made once every 15 days from June 1 through September 1. The irrigation treatment has been repeated each growing season since. The total quantity of water applied, 35 area cm per annum, is approximately equal to the average annual precipitation on the site during the frost free period. The fertilizer–irrigation treatments and the experimental design have been described previously (Leaf and Leonard 1967; Leaf *et al.* 1970). The original experiment was installed in two adjoining stands on the southern end of the plain described by Heiberg and Loewenstein (1958). The stands were chosen because of the considerable differences in productivity between them. The four experimental treatments, control (C), irrigation (I), fertilization (F), and combined irrigation–fertilization (IF) were each represented in both stands. The present study which was conducted in the summer of 1971, was confined to the stand of lower productivity, described as 'poor' in descriptions of the study area (Heiberg and Loewenstein 1958; Leaf and Leonard 1967; Leaf *et al.* 1970).

A 50 cm length of metal conduit tubing, sharpened at one end, was used as a soil sampler. The tube was 5.2 cm in diameter giving a volume to 15 cm of 318 cm^3. On each of six collection dates, between mid-July and late-August, samples were taken, after removal of the L layer, at 0–15 cm and 15–30 cm depths from one randomly selected sampling point in each plot. Samples were kept in cold storage until root removal was begun. Root removal was by a combined dry and wet sieving procedure, using a nest of three sieves (4.0 mm, 2.0 mm, and 841 μm). The entire sample was placed on the 4.0 mm sieve and gently shaken manually. When free of most mineral matter, the roots on the 4.0 and 2.0 mm sieves were transferred to petri dishes and further separation of roots from soil was carried out in water. Root material on the 841 μm sieve was recovered by washing the sieve free of as much mineral matter as possible. Careful examination of the material washed through this sieve, and the material in the receiving pan, revealed no intact root tips. Root material was stored in a solution of alcohol – glacial acetic acid – formaldehyde (FAA) for classification and counting of root tips.

Intact root tips only, *i.e.* those with a wholly intact apex, were counted. Each apex of an apparently ectomycorrhizal structure was counted as a separate root tip. All root tips not shrivelled or dissicated were considered living. Tips were classified on the basis of morphological characteristics as active, dormant, or black. Counting and classification of root tips was done with a binocular microscope. Tips which were white or yellow in color were considered active. They were translucent, relative to dormant roots, had firm, sharp outlines, and generally possessed the appearance of recent growth. The term 'dormant' was used to cover light brown or brown roots with brown or sharply delimited, inconspicuous white apices (Wilcox 1964). Black root tips were those invaded by a black fungus for over 50% of their surface area. The form of black mycorrhiza most commonly encountered was identified from the description given by Harley (1969) as *Cenococcum graniforme* (Sow.) Ferd. and Winge. This category of root tip did not represent the only mycorrhizal structure present. Over 40% of all root tips classified as active or dormant were apices of dichotomously branched structures.

Black root tips were included as a separate class because they were so numerous and because, where present, they made it impossible to distinguish between active and dormant roots. This represented a serious difficulty in the classification of the root tips and contributed to the considerable varitaion recorded in the active and dormant classes. Infection, resulting in black root tips, appeared to be both primary and secondary. The fungus was present on both branched and unbranched root tips, whether active or dormant, senescent, or even apparently dead.

It was considered undesirable, due to possible deterioration of the roots, to keep soil samples in storage for longer than 1 week before separation. No significant variation in the data due to the time of collection of the sample was detected. The data were pooled and the values discussed each represent the means of six samples. The Scheffé Test for multiple comparisons was used to compare treatment effects for dormant, active, black, and total numbers of root tips at each soil depth level. Sample size (n) calculations were made for two sets of treatment comparisons by the formulae:

$$n_1 = ((S_1^2 + S_1S_2)/\varepsilon_1\varepsilon_2)(t_{\alpha/2} + t_\beta)^2$$

and

$$n_2 = ((S_2^2 + S_1S_2)/\varepsilon_1\varepsilon_2)(t_{\alpha/2} + t_\beta)^2$$

where: S = standard deviation of sample;
S^2 = variance estimate;
t = Student's t value;
ε = allowable error, taken as 10% of population mean;
α = probability of Type I error (Steel and Torrie 1960), taken at 0.05; and
β = probability of Type II error, taken at 0.20.

Results

Numbers of root tips were approximately 10 times greater at the 0–15 cm than at the 15–30 cm soil depth (Table 1). No significant differences among treatments were recorded at the 15–30 cm soil depth. Throughout, root tip numbers reached their maxima under the irrigation-only treatment and their minima under the fertilization-only treatment. The irrigated trees received 35 cm of water from June 1 through September 1 in addition to the frost-free precipitation each year. The frost-free precipitation, or May through September precipitation, ranged from about 40 to 50 cm during 5 years prior to this investigation, and was 51.9 cm for the year of this study (Table 2). Significant differences were recorded only at the 0–15 cm depth in the dormant class and in total numbers: irrigation *versus* fertilization, and irrigation *versus* irrigation and fertilization.

The effect of irrigation on soil moisture in the upper horizons of the profile is quite short lived. Intensive monitoring of soil moisture at short time intervals indicated that the moisture level in the upper 60 cm of soil returned almost to pretreatment levels within 48 h of the start of irrigation treatment (Leaf *et al.* 1970).

This pattern of response to treatment does not correspond to the measured response in above-ground stem volume increment presented in Table 2. Irrigation alone had little effect on this volume increment. In a study of soil microarthropod populations on the same plots, however, irrigation had the greatest effect on microarthropods, increasing their total numbers and altering population composition (Carey 1972).

Discussion

Allowing for interception losses of precipitation by the forest canopy, irrigation more than doubled the quantity of water reaching the forest floor during the months, June, July, and

TABLE 1. Effects of irrigation (I), fertilization (F), and combination (IF) on numbers of root tips per square centimeter surface soil, 0–15 and 15–30 cm depth

Treatments	Root classes			
	Dormant	Active	Black	Total
Mean numbers (0–15 cm)				
None (C)	20.2	18.3	13.5	52.0
I	34.1	25.0	20.4	79.5
F	9.8	11.7	6.5	28.0
IF	9.3	10.7	11.5	31.5
Standard error of treatment mean	±5.80	±4.67	±4.42	±10.32
Mean numbers (15–30 cm)				
None (C)	1.5	1.5	1.0	4.0
I	4.1	3.7	1.5	9.3
F	1.0	2.2	0.5	3.7
IF	1.0	2.2	1.8	5.0
Standard error of treatment mean	±1.05	±0.95	±1.05	±2.04
Significant treatment effect comparisons	Level of significance[a]			
0–15 cm soil depth only:				
I *versus* F	*			**
I *versus* IF	*			**
(F + IF) *versus* (C + I)	*			**

[a] Significance levels: * = 0.10 level; ** = 0.05 level.

August. Measurements of soil moisture characteristics indicate that the solum is capable of retaining the applied water against deep seepage (Leonard *et al.* 1971). This is supported by empirical evidence from a nearby area (Eschner and Leonard 1968). Positive confirmation of a growth restricting moisture deficiency in the study area can only be obtained by direct experimental evidence. While the results obtained to date are inconclusive (Table 2), Jurgensen and Leaf (1965) have demonstrated a significant inverse relationship between stand basal area and depth to water table for red pine on an adjoining soil series of the same family.

TABLE 2. Annual total stem volume increment in control (C), irrigated (I), fertilized (F), and combined treatment (IF) plots from 1966, year of initiation of treatments, through 1969; and frost-free season precipitation during 1966 through 1970

Year	Stem volume increment (m^3/ha) for plot treatments				Frost-free season precipitation (cm)
	C	I	F	IF	
1966	4.0	4.0	4.1	3.8	45.9
1967	4.4	4.7	6.7	6.9	46.1
1968	5.4	6.6	10.1	10.9	45.8
1969	7.1	8.6	16.0	17.8	40.8
1970	—	—	—	—	49.8

NOTE: Volume data after R. Wittwer 1972. Red pine growth response to fertilization and/or irrigation treatments. M.S. thesis. State University of New York College of Environmental Science and Forestry, Syracuse, New York, N.Y.

Interpretation of the influence of irrigation on root tip numbers is complicated by the effect of the treatment on soil temperature. In 1967, during the period June 1 to September 1, soil temperature at 5 cm depth ranged from 8.0 °C at the beginning of June to 15.5 °C in July (Leonard *et al.* 1971). The temperature of the irrigation water was from 0 to 5.5 °C above the temperature of the soil at 5 cm depth. While irrigation-induced temperature fluctuations in the upper 30 cm of this soil are essentially ephemeral, the accumulated heat sum expressed on a weekly basis has been demonstrated to be significantly greater in irrigated than in non-irrigated plots (Leonard *et al.* 1971).

The sensitivity of root growth to temperature changes in the growth medium has been demonstrated for many species (Grobbelaar 1963; Brouwer and Hoogland 1964; Lyr and Hoffman 1967; Kramer 1969). Small changes in temperature can affect root growth (Walker 1969) and mycorrhizal development (Theodorou and Bowen 1971). Complex changes have been observed in red pine root and mycorrhizal development at temperatures between 15 and 27 °C (H. E. Wilcox, personal communication, State University of New York College of Environmental Science and Forestry, Syracuse, New York). The increased numbers of root tips in irrigated plots may be in part a temperature induced response to irrigation. The literature on gross root morphology, with its many references to prolific rooting in soil horizons possessing good physical or chemical characteristics (Moore 1922; Weaver 1926; Büsgen and Münch 1929; Coile 1937; Bishop 1962), supports the view that the roots in the upper 30 cm of soil are responding to their immediate environment and are not significantly influenced by treatment induced moisture and temperature changes which have been reported occurring deeper in the soil profile (Leonard *et al.* 1971).

The experiment was not designed to give information on the rate of root production. The greater root numbers in irrigated plots may be a reflection of increased root longevity under this treatment, while fertilization may promote the more rapid senescence and, presumably, decomposition of roots.

Despite the high level of consistency observed in the results, few statistically significant differences between treatments were recorded. This can reasonably be explained by the considerable variation experienced within treatments. The contribution of the ectotrophic mycorrhiza *Cenococcum graniforme* to this variation has already been discussed. Calculated sampling intensity for two sets of treatment comparisons at specific levels of probabilities (α and β) and allowable sampling error (ϵ), indicate the need for very high numbers of samples (Table 3). This is a reflection of natural variation in the sampled population. In a separate investigation conducted on 1-0 nursery grown seedlings of six coniferous species, numbers of root branches also showed great variation (E. P. Farrell, unpublished data).

The difficulty with the technique adopted in this study is that fine roots are apparently very sensitive to conditions in their immediate environment and investigation is inevitably hampered by temporal and spatial limitations in a dynamic system. While the feasibility of accurately quantifying numbers of root tips under field conditions may be questioned, it seems likely that this parameter of root growth is a more realistic measure of response to cultural treatment than any expression of gross root characteristics, such as weight, by arbitrarily defined diameter classes.

TABLE 3. Coefficients of variation (CV) for numbers of root tips per square centimeter surface soil, 0–15 cm depth, and calculated sampling intensity (n)[a] for irrigated (I) *versus* control (C), and fertilized (F) *versus* control (C) plot comparisons

		Plot treatments			
		I *versus* C		F *versus* C	
Root class	CV (%)	nI	nC	nF	nC
Dormant	77.5	341	199	196	384
Active	69.7	322	274	169	386
Black	83.7	646	600	1015	1761
Total	52.9	457	236	239	371

[a] At levels of probabilities and allowable sampling errors of: $\alpha = 0.05$; $\beta = 0.20$; and $\varepsilon = 10\% \bar{X}$.

It is the dilemma of the research in this area to harmonize the sensitivity of the measurement of site characteristics with the sensitivity of the plant's response to change.

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